HOMs IN VELOCITY-OF-LIGHT SPOKE CAVITIES

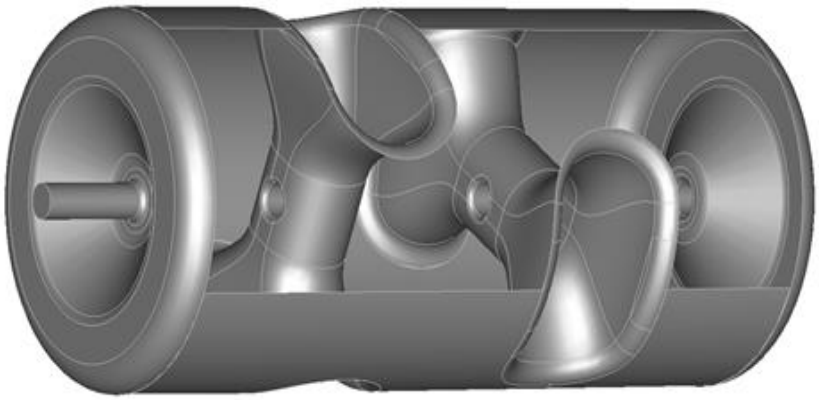
Christopher Hopper

Center for Accelerator Science
Old Dominion University
Department of Physics
and
Thomas Jefferson National Accelerator Facility

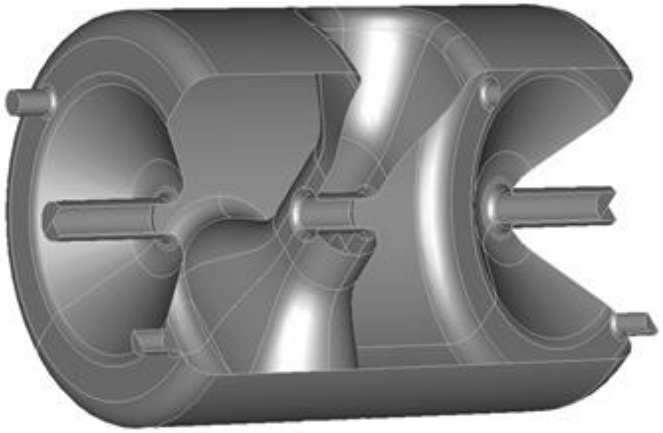
TOPICS COVERED TODAY…

- Introduction
- Mode Types
- [R/Q], $[R/Q]_T$ Calculations
- Velocity Dependence
- HOM Damping

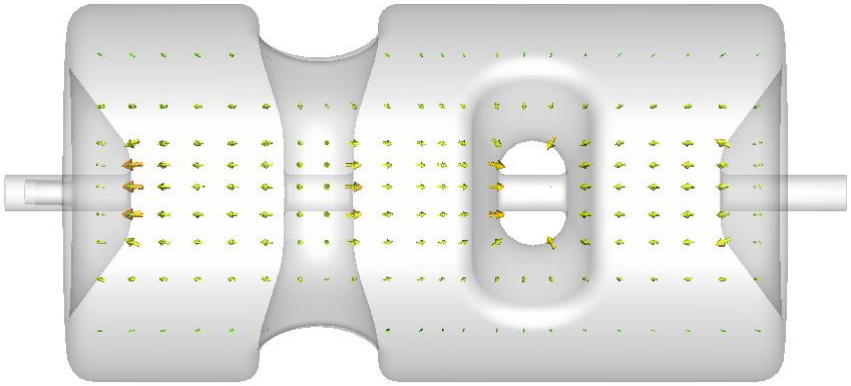
HIGH-VELOCITY SPOKE CAVITIES

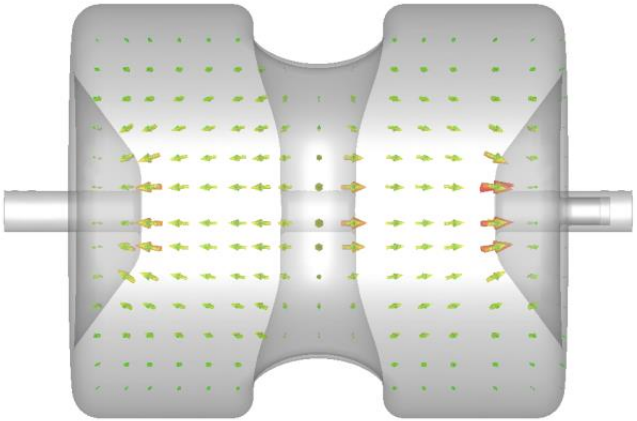


500 MHz, β_0 = 1 double-spoke cavity



325 MHz, β_0 = 0.82 single-spoke cavity

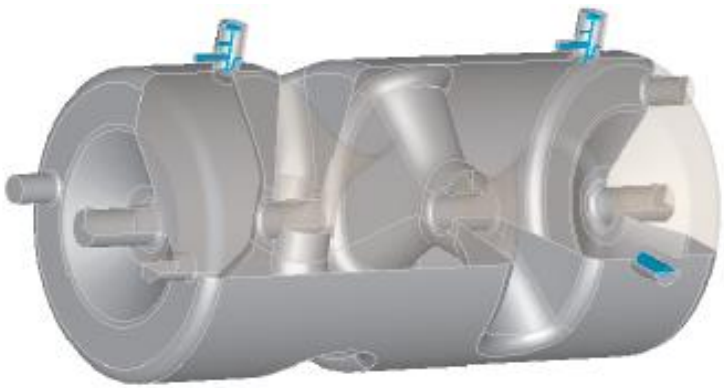


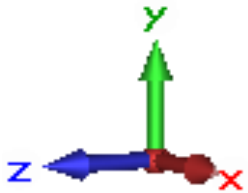


TEM-Class, Accelerating Cavities

TERMINOLOGY

- The beam travels along the *z* axis. Transverse directions are *x* and *y*, which run parallel to the spoke(s).
- Accelerating modes are those where $E_z(z)$, along the beam axis, is greater than $E_x(z)$ and $E_y(z)$.
- Deflecting modes are those where either $E_x(z)$ or $E_y(z)$ are greater than $E_z(z)$.
- φ is the phase between the particle and the rf fields. When considered in a calculation of [R/Q], $[R/Q]_T$, the value φ of is that which maximizes the voltage.

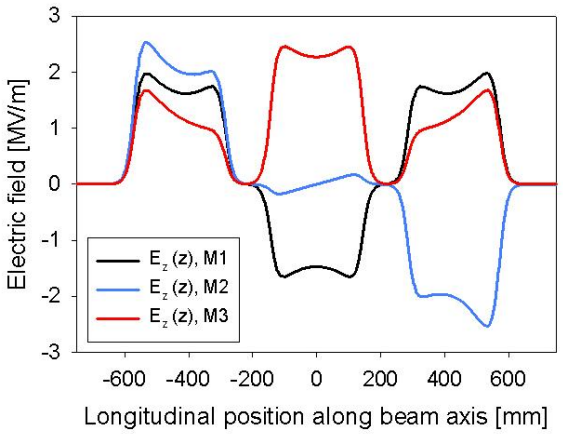




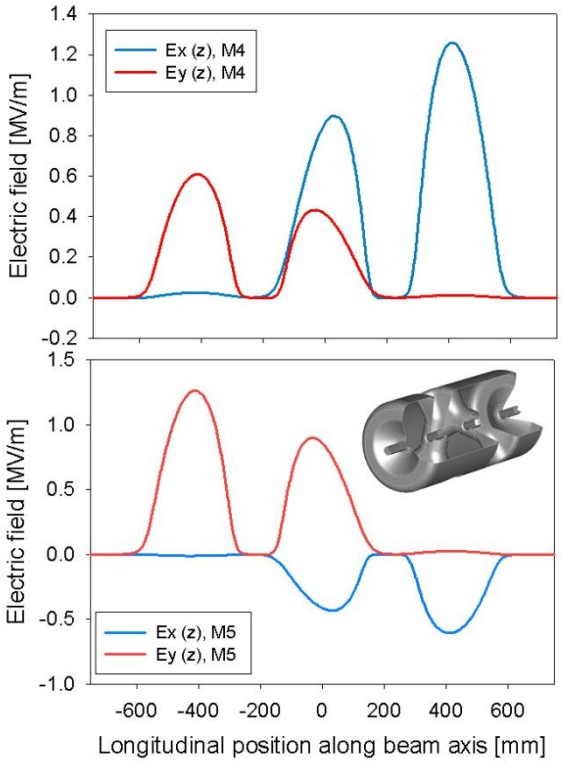
- Introduction
- Mode Types
- [R/Q], $[R/Q]_T$ Calculations
- Velocity Dependence
- HOM Damping

MODE TYPES (DOUBLE-SPOKE)

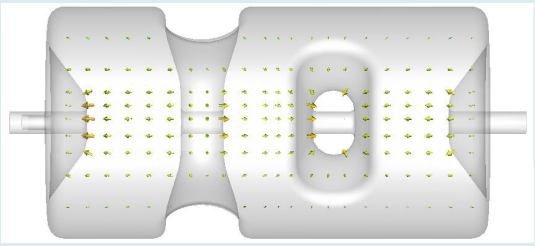
Accelerating modes



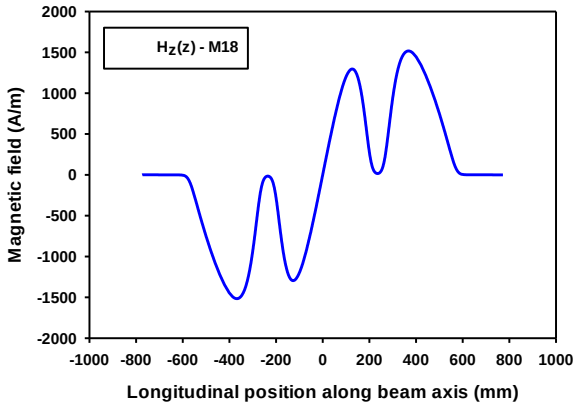
Deflecting Modes (degenerate) modes



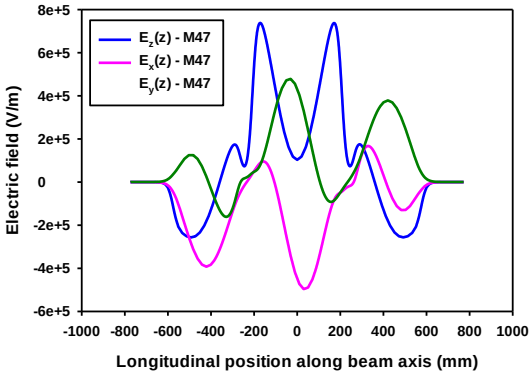
Examples of modes for the 325 MHz cavity, β_0 =1



TE-type modes

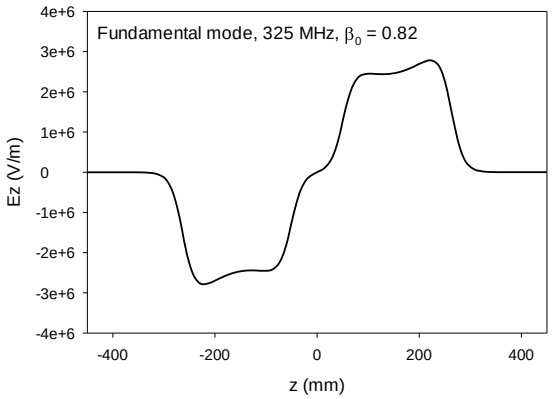


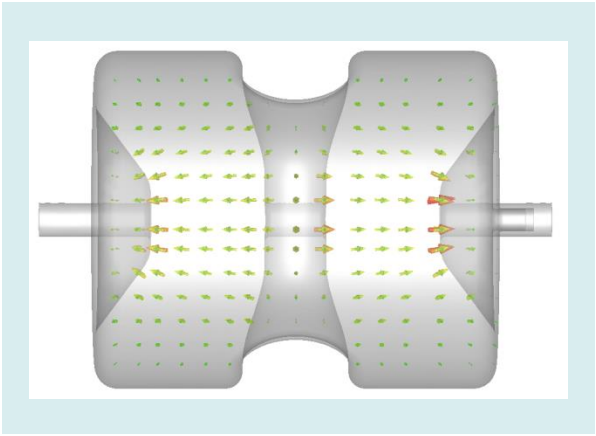
Hybrid modes



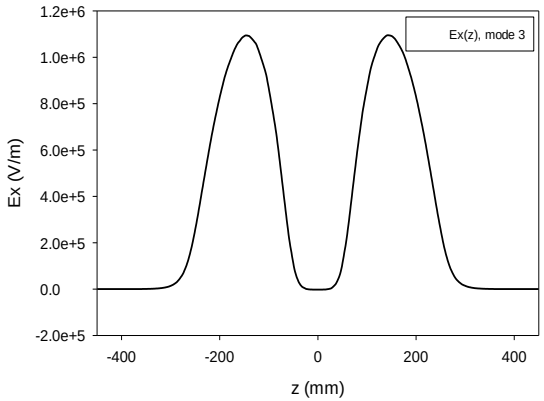
MODE TYPES (SINGLE-SPOKE)

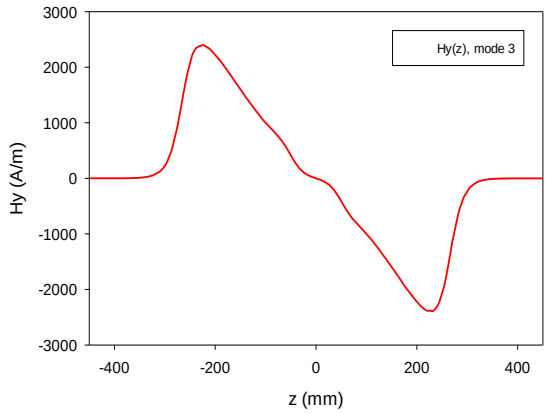
Accelerating modes



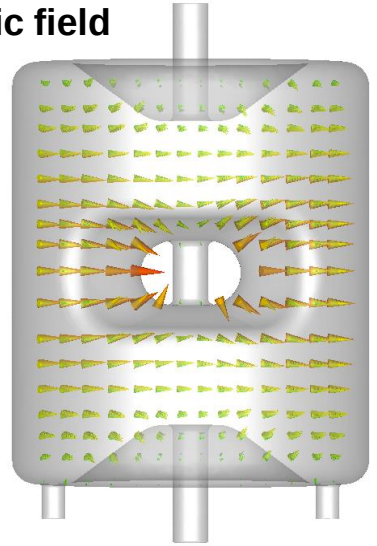


Deflecting modes

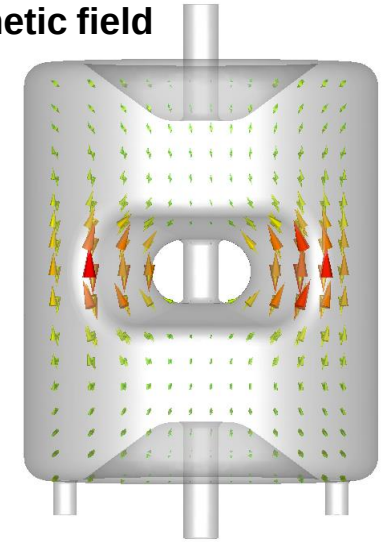




Electric field



Magnetic field



- Introduction
- Mode Types
- [R/Q], $[R/Q]_T$ Calculations
- Velocity Dependence
- HOM Damping

CALCULATING [R/Q], $[R/Q]_T$

Accelerating Modes

$$\left(\frac{R}{Q}\right) = \frac{V_{acc}^2}{\omega_n U}$$

$$V_{acc} = \left|\int_{-\infty}^{\infty} E_z(z, r=0)\cos\left(\frac{\omega z}{\beta c} + \varphi\right) dz\right|$$

$$\left(\frac{R}{Q}\right) = \left.\frac{\left|\int_{-\infty}^{\infty} E_z(z, r=0)\cos\left(\frac{\omega z}{\beta c} + \varphi\right) dz\right|^2}{\boldsymbol{\omega_n U}}\right|_{\boldsymbol{max\ \varphi}}$$

Deflecting Modes

$$\left(\frac{R}{Q}\right)_\perp = \left.\frac{\left|\int_{-\infty}^{+\infty}\left(\vec{E}_\perp(z, r=0) + i(\vec{v}_z \times \vec{B}_\perp)\right) e^{i\left(\frac{\omega_n z}{\beta c} + \varphi\right)} dz\right|^2}{\omega_n U}\right|_{max\varphi}$$

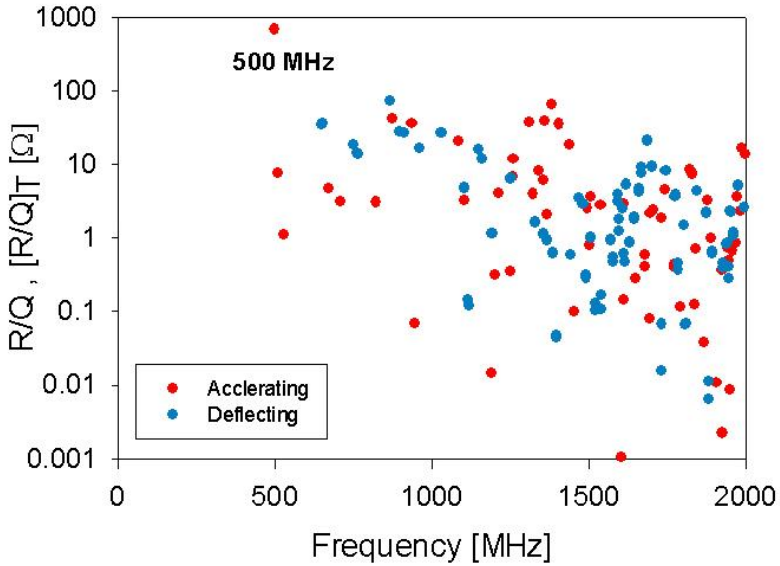
Verify with PWT

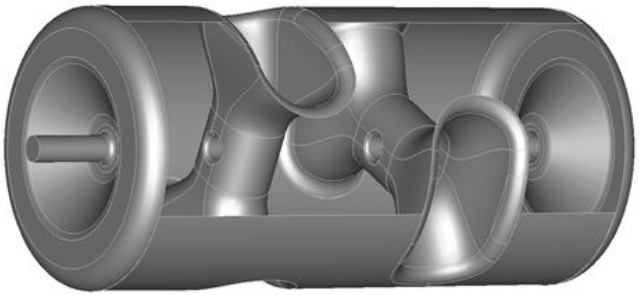
$$\Delta p_\perp = \left(\frac{e}{\omega_n}\right)\int_0^L (-i)\nabla_\perp E_z dz$$

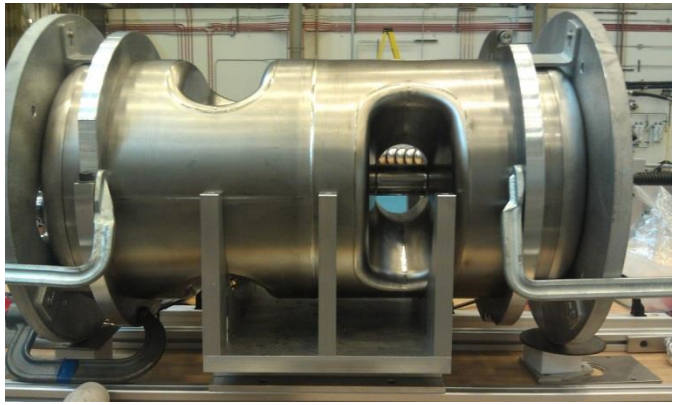
$$\left(\frac{R}{Q}\right)_\perp = \lim_{a\to 0} \left.\frac{\left|\int_{-\infty}^{+\infty}\left(\vec{E}_\perp(z, r=0) + i(\vec{v}_z \times \vec{B}_\perp)\right) e^{i\left(\frac{\omega_n z}{\beta c} + \varphi\right)} dz\right|^2}{(k_n a)^2 \omega_n U}\right|_{max\varphi}$$

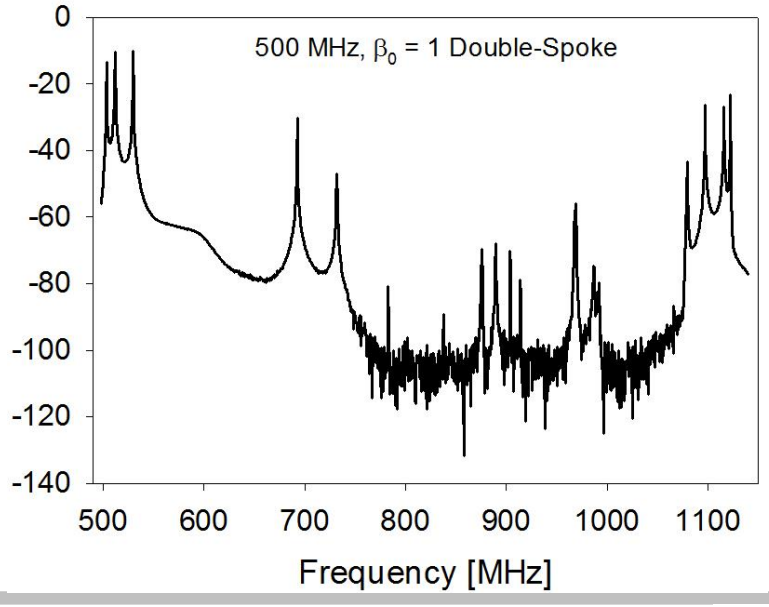
[R/Q] VALUES OF HOMs

[R/Q] values for particles at design velocity $\beta_0 = 1$ for the 500 MHz double-spoke cavity

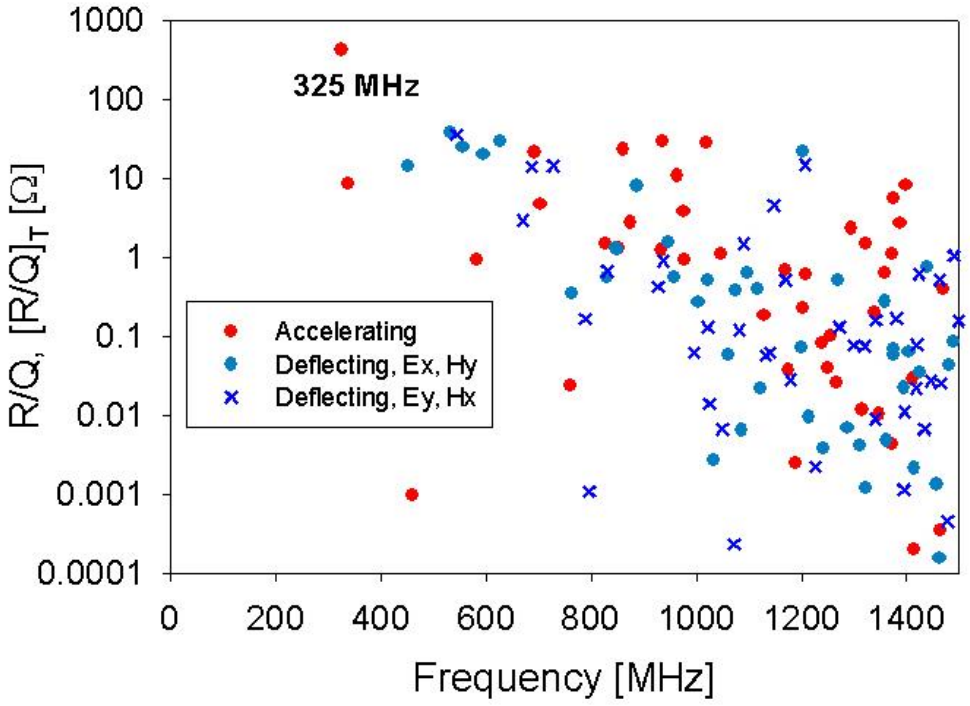




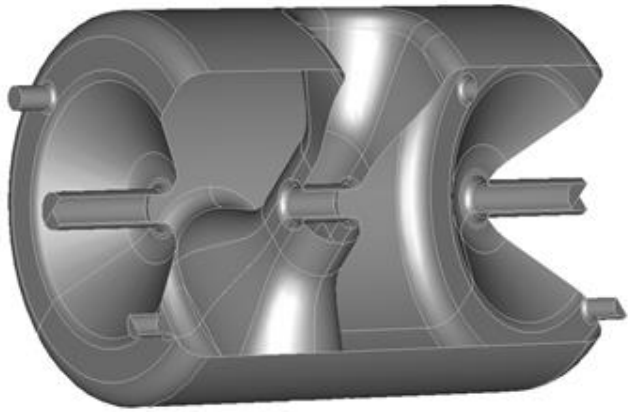




[R/Q] Values of HOMs



[R/Q] values for particles at design velocity $\beta_0 = 0.82$ for the 325 MHz single-spoke cavity



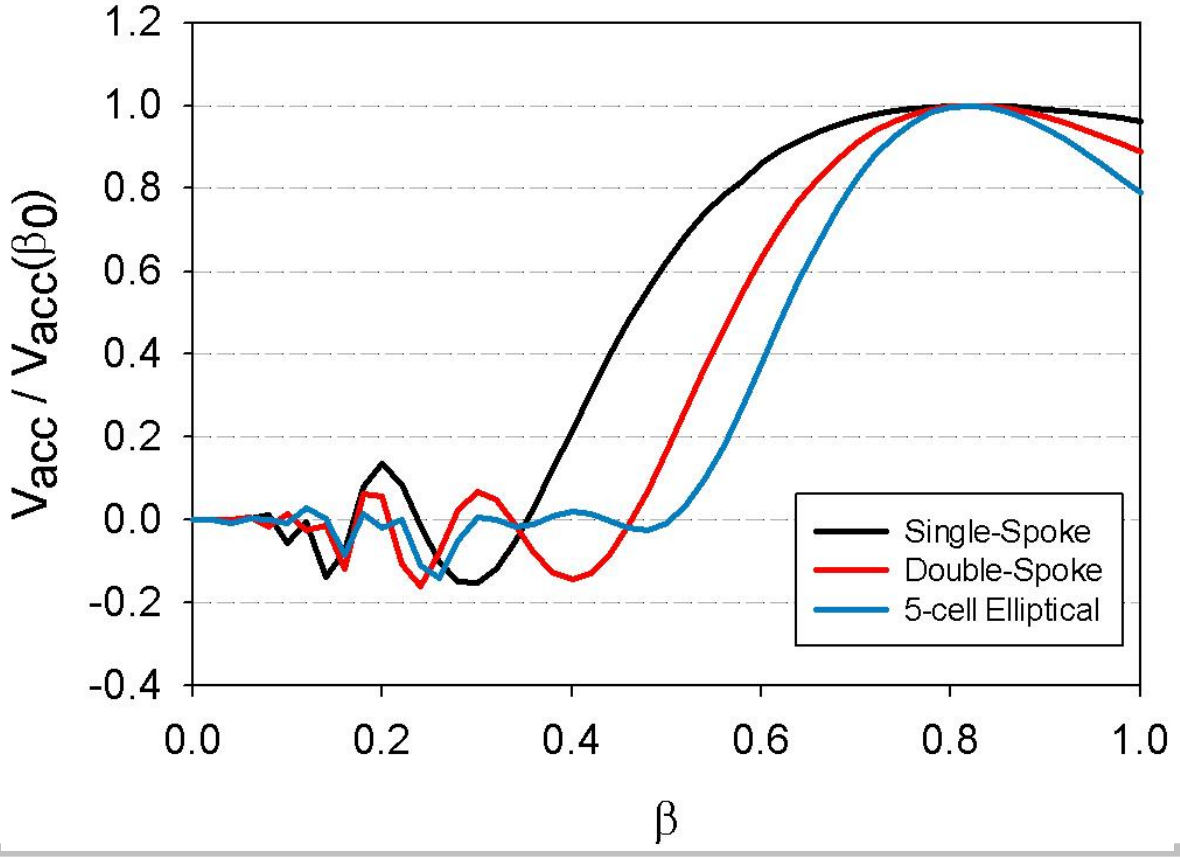
325 MHz, $\beta_0 = 0.82$ single-spoke cavity

- Introduction
- Mode Types
- $[R/Q]$, $[R/Q]_T$ Calculations
- Velocity Dependence
- HOM Damping

VELOCITY ACCEPTANCE

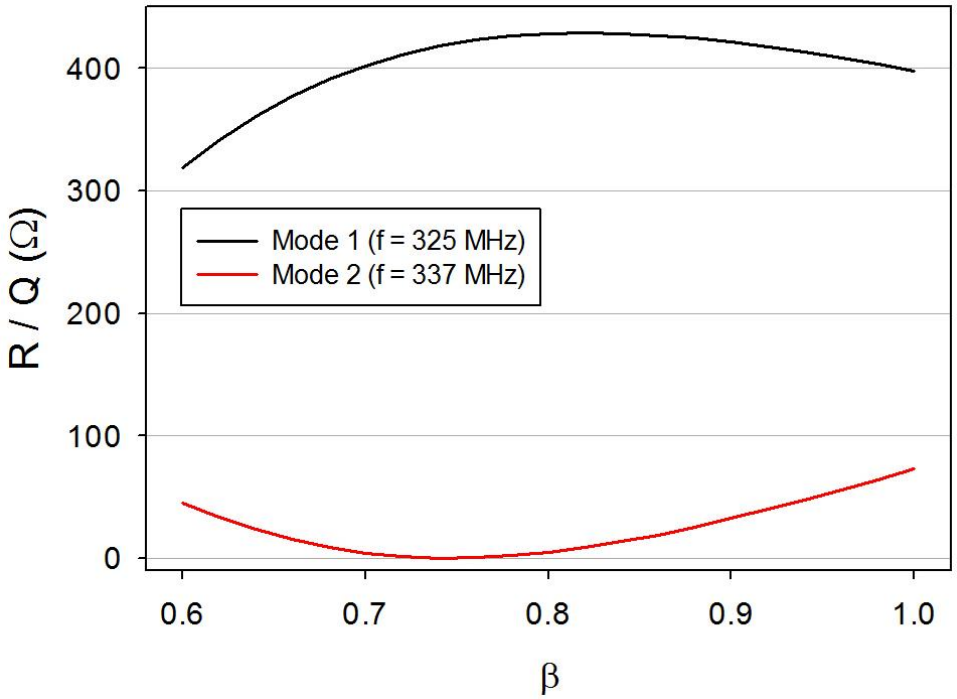
- Single-spoke cavity: Greater than 96% efficiency between $0.7 \leq \beta \leq 1$.
- This corresponds to protons with energies between 380 MeV and > 1.5 GeV

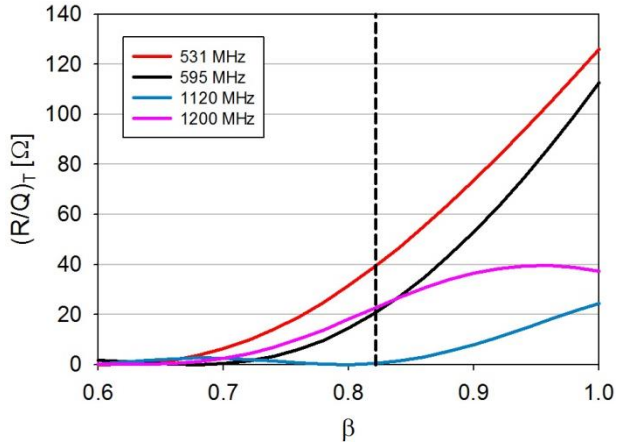
- Double-spoke cavity: Greater than 96% efficiency between $0.74 \leq \beta \leq 0.92$.
- This corresponds to protons with energies between 460 MeV and 1.5 GeV



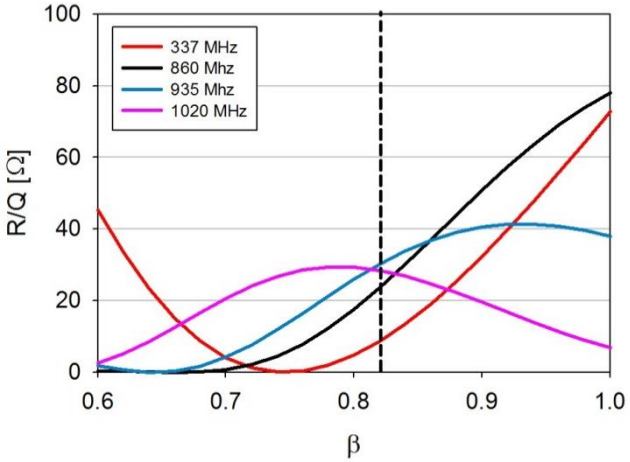
VELOCITY DEPENDENCE (SINGLE-SPOKE)

325 MHz, β_0 = 0.82 single-spoke cavity (R/Q = 450 Ω)





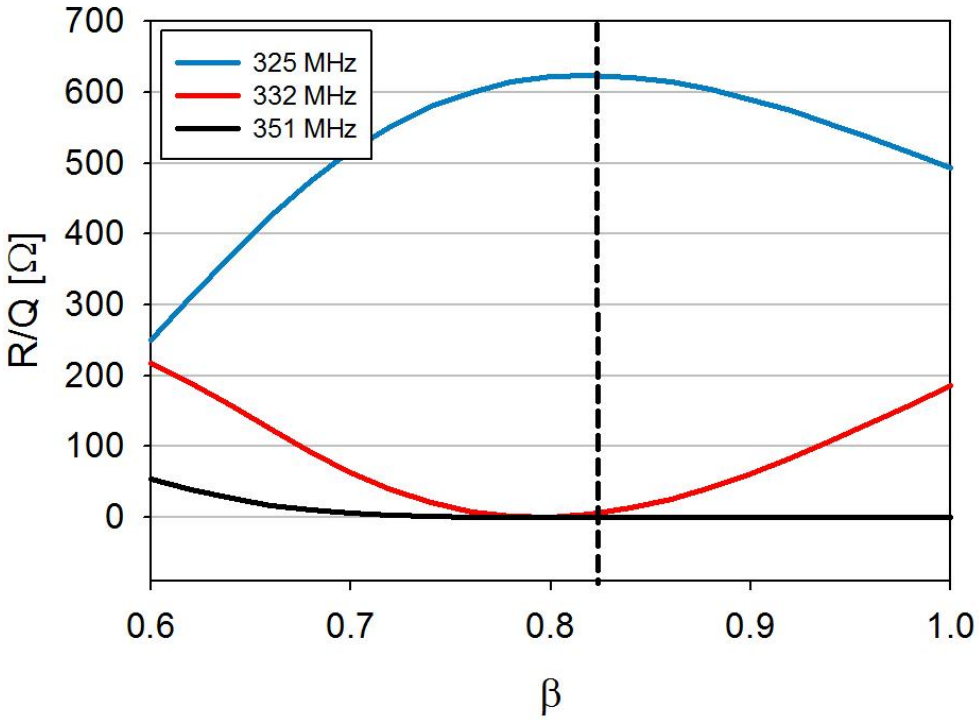
Deflecting Modes

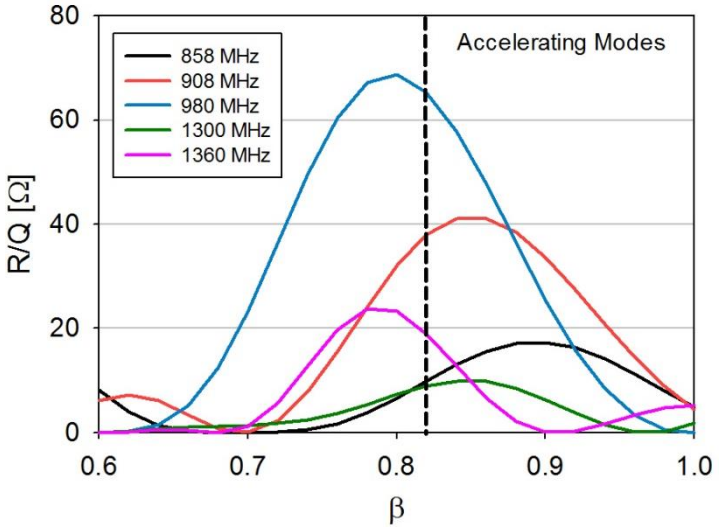


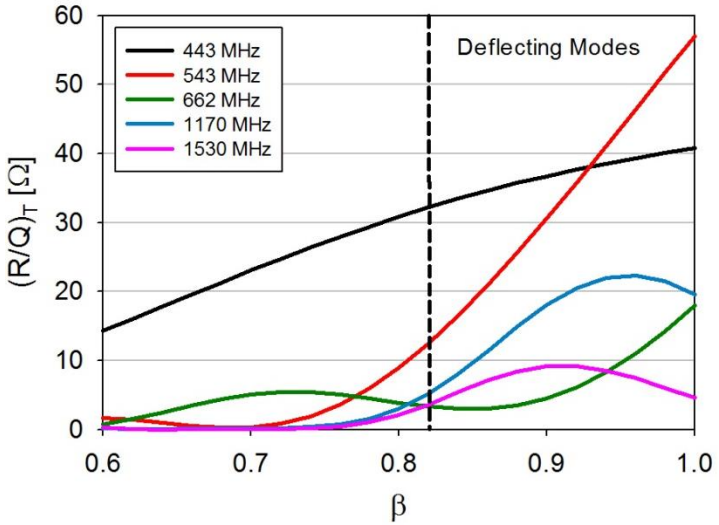
Accelerating Modes

VELOCITY DEPENDENCE (DOUBLE-SPOKE)

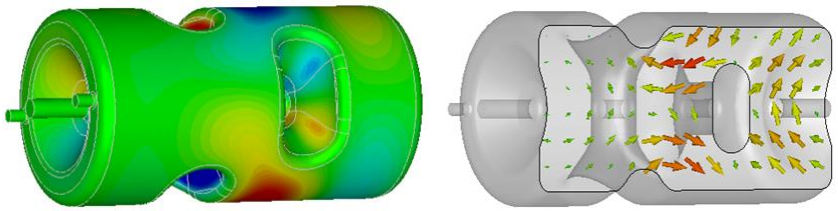
325 MHz, β_0 = 0.82 double-spoke cavity
(R/Q = 625 Ω)

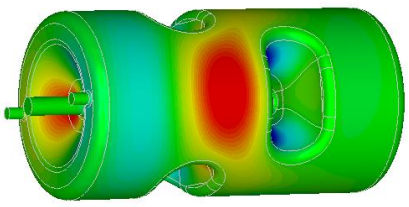


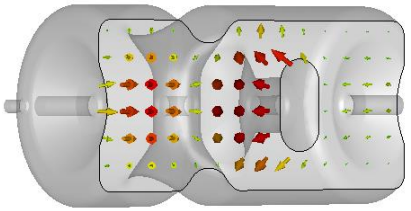


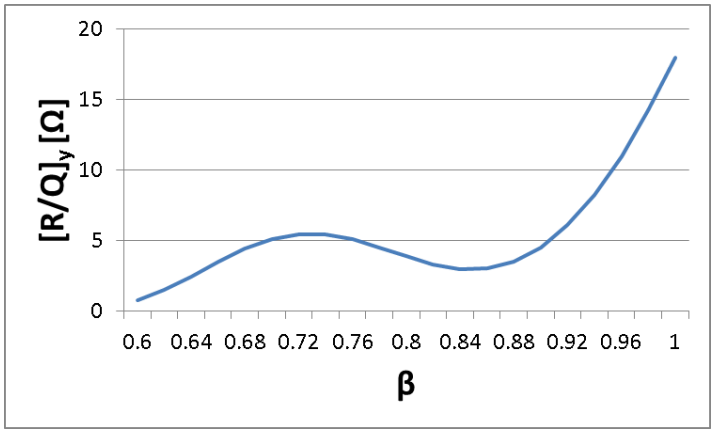


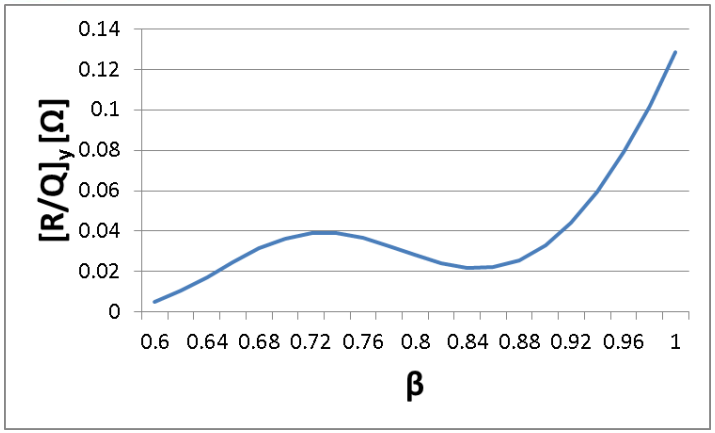
f = 662 MHz DEGENERATE MODE

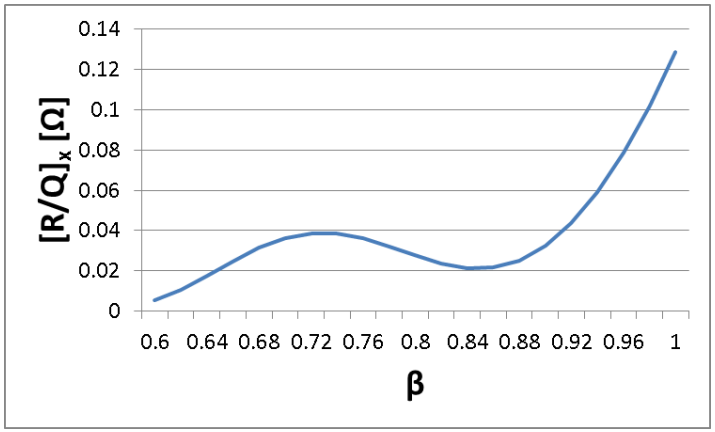


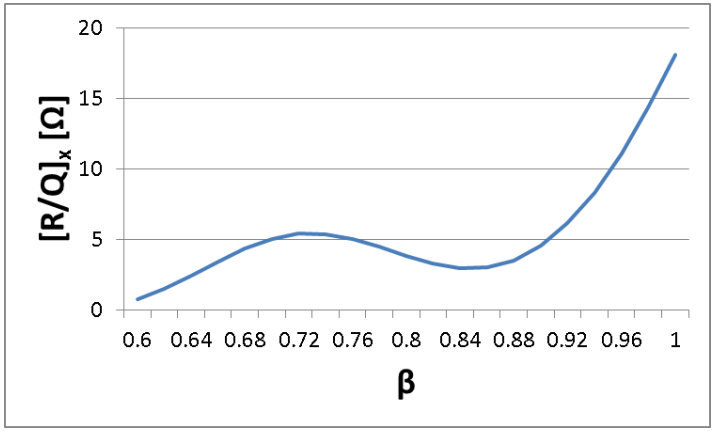




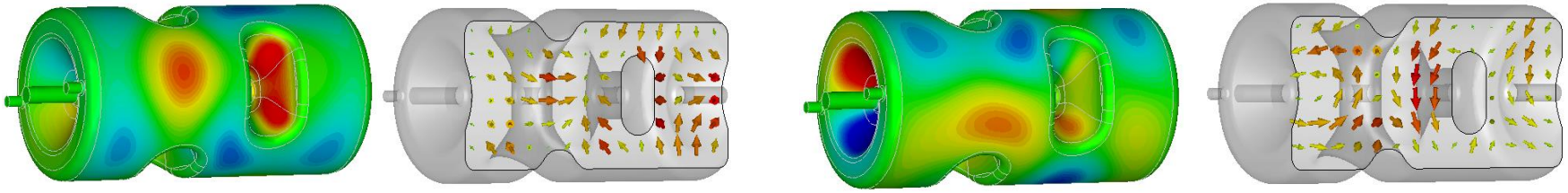


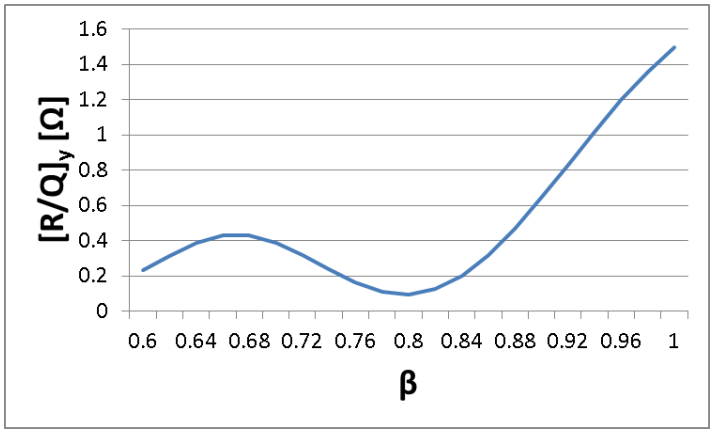


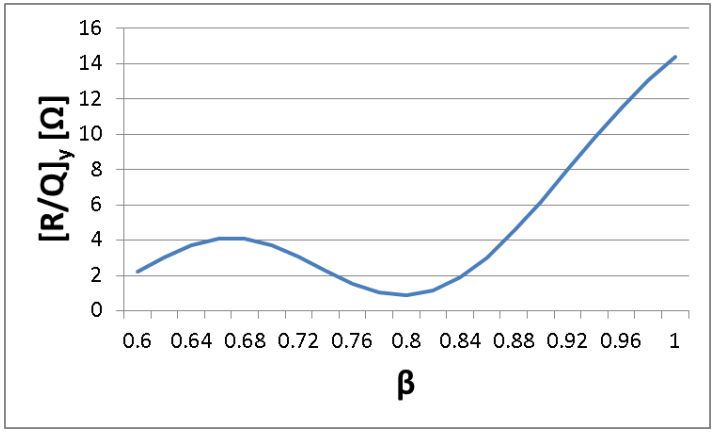


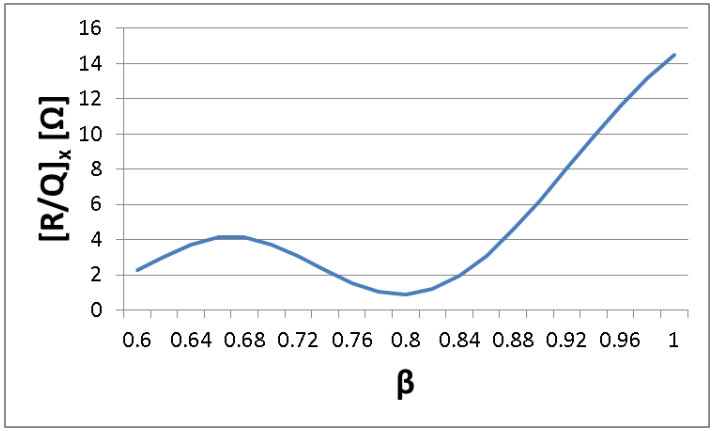


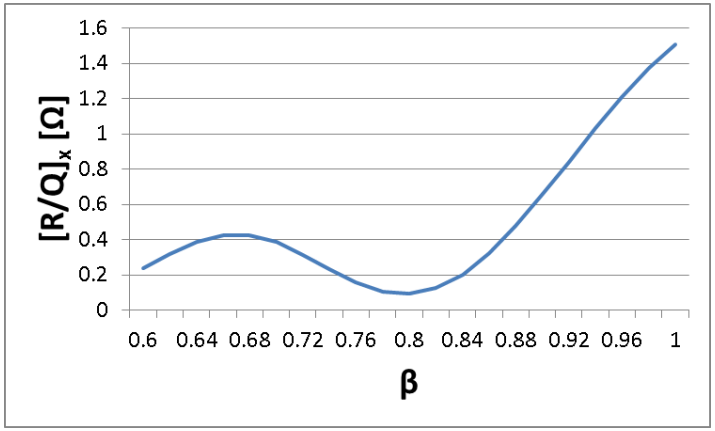
f = 727 MHz DEGENERATE MODE



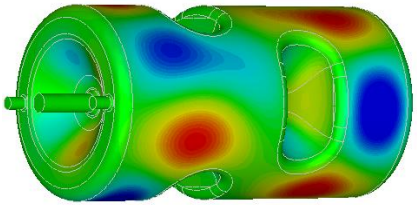
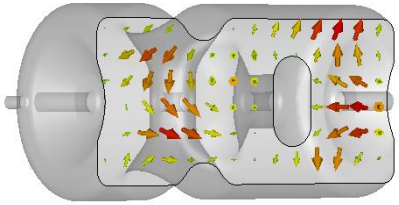
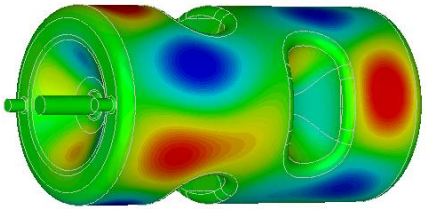
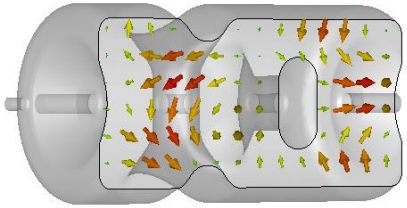


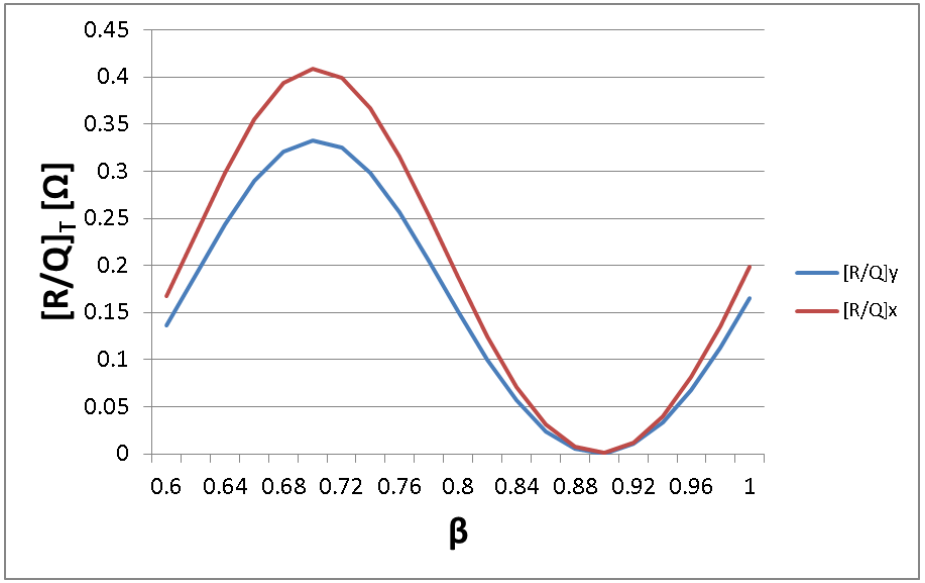


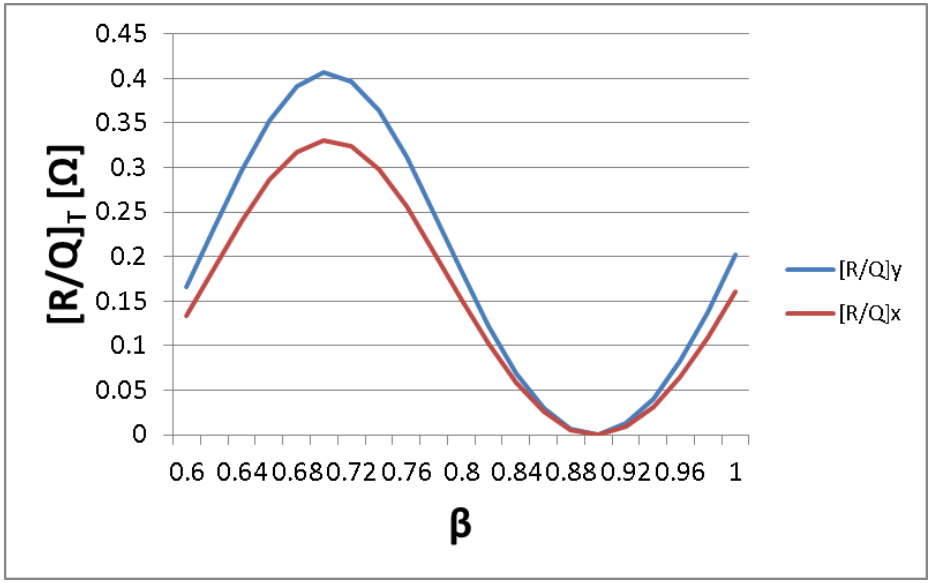




f = 770 MHz DEGENERATE MODE





- Introduction
- Mode Types
- $[R/Q]$, $[R/Q]_T$ Calculations
- Velocity Dependence
- HOM Damping

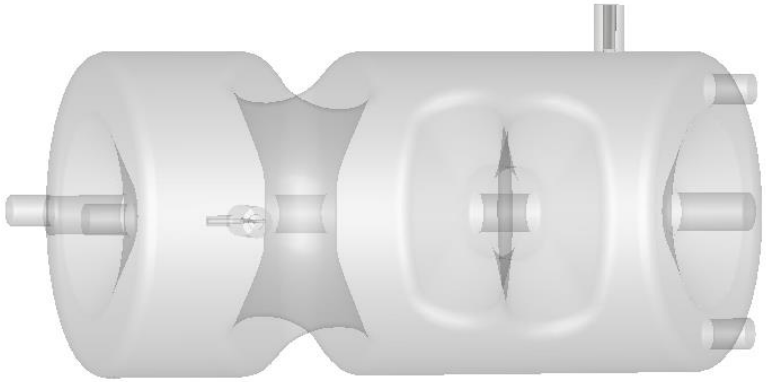
500 MHz β_0 = 1 DOUBLE-SPOKE

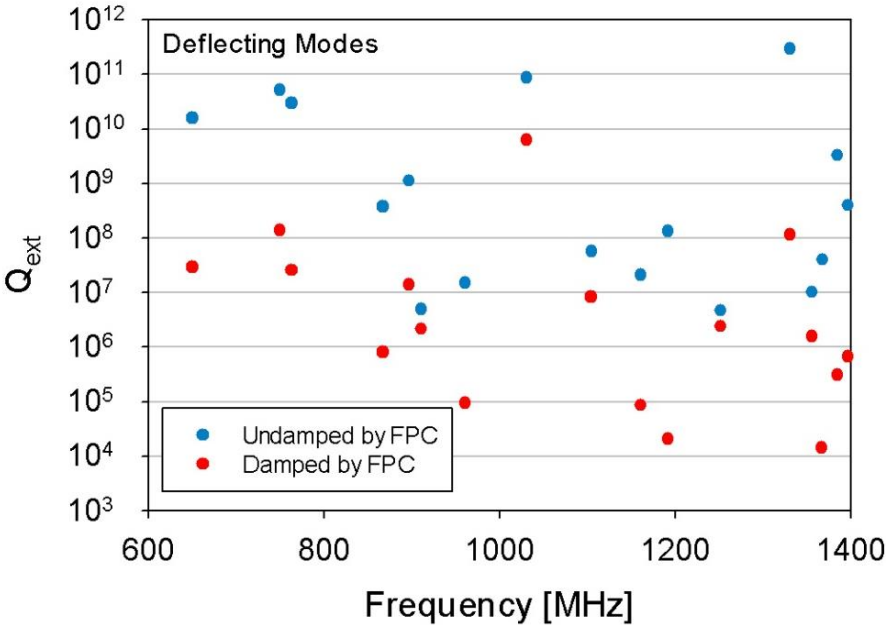
- Compact light source using 4 double-spoke cavities to accelerate electrons from 2 – 25 MeV

- Prototype currently being fabricated in an ODU/Jlab collaboration.

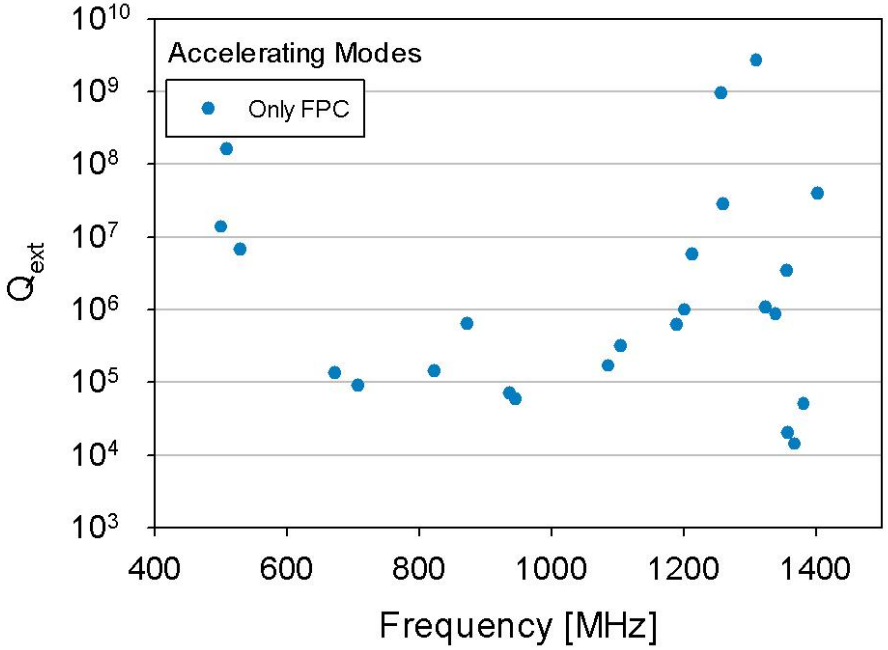
Parameter	Value	Units
Bunch Charge	10	pC
Rep. Rate	100	MHz
f_{rf}	500	MHz
Beam Current	1	mA
Bunch Length	0.9 (3)	mm (psec)
Cavity Voltage V_{acc}	6	MV
Quality Factor Q_0	1.5×10^9	-

FUNDAMENTAL POWER COUPLER





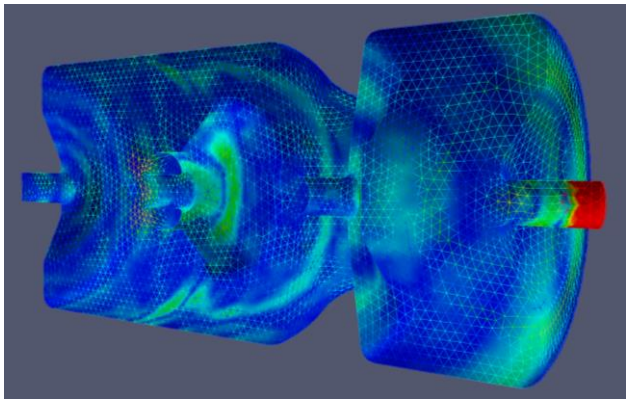
The optimal loaded quality factor is ~ 1 x 10^7.



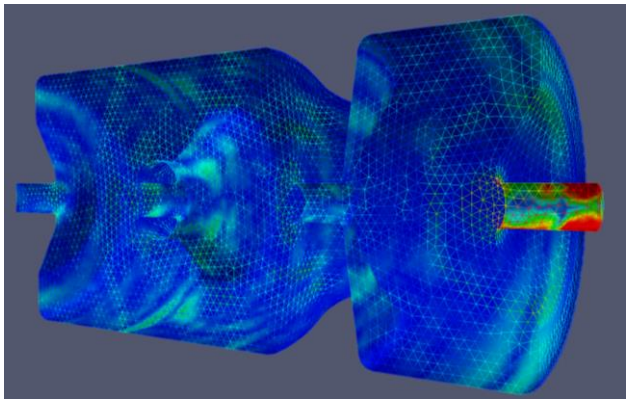
Some HOMs strongly couple to the FPC, however the load is only matched to the fundamental mode.

UNDAMPED MODES

Frequency [MHz]	(R/Q) [Ω]	Q_{ext}
1256	7	9×10^{8}
1260	12	2.7×10^{9}
1310	38	2.8×10^{7}
1403	36	4×10^{7}

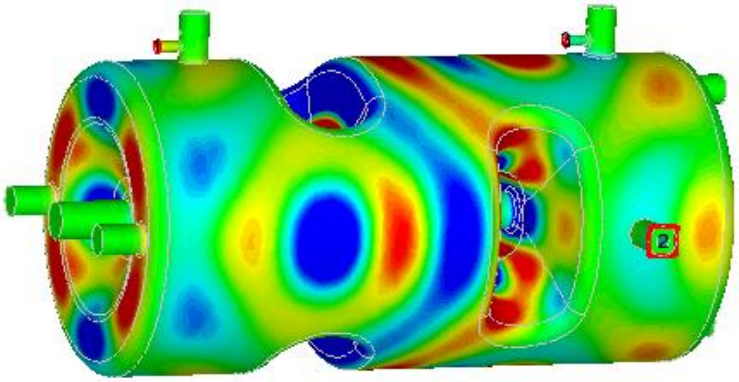


Frequency [MHz]	(R/Q) [Ω]	Q_{ext}
650	36	1.6×10^{10}
749	19	5.2×10^{10}
763	16	3×10^{10}
897	28	1.1×10^{9}
1030	27	8.7×10^{10}



SURFACE FIELDS

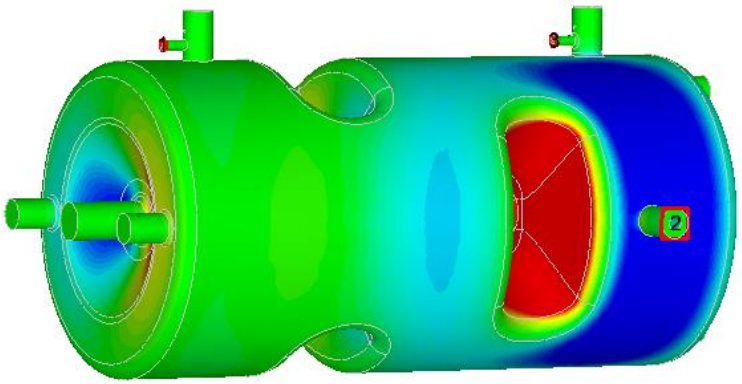
Surface electric field

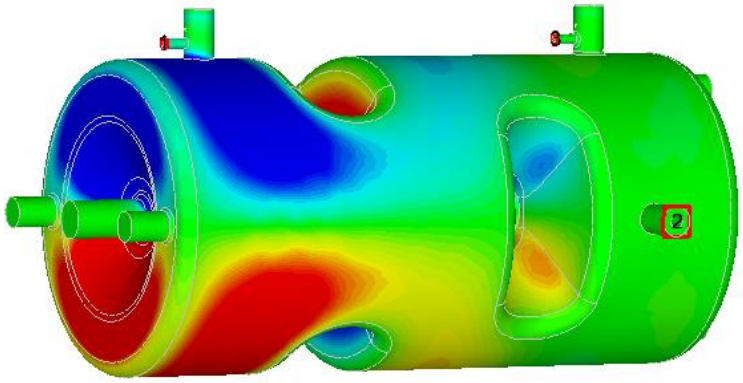


1999 MHz Accelerating Mode

Various coupler placements need to be tried to effectively couple to the most dangerous modes

Surface electric field

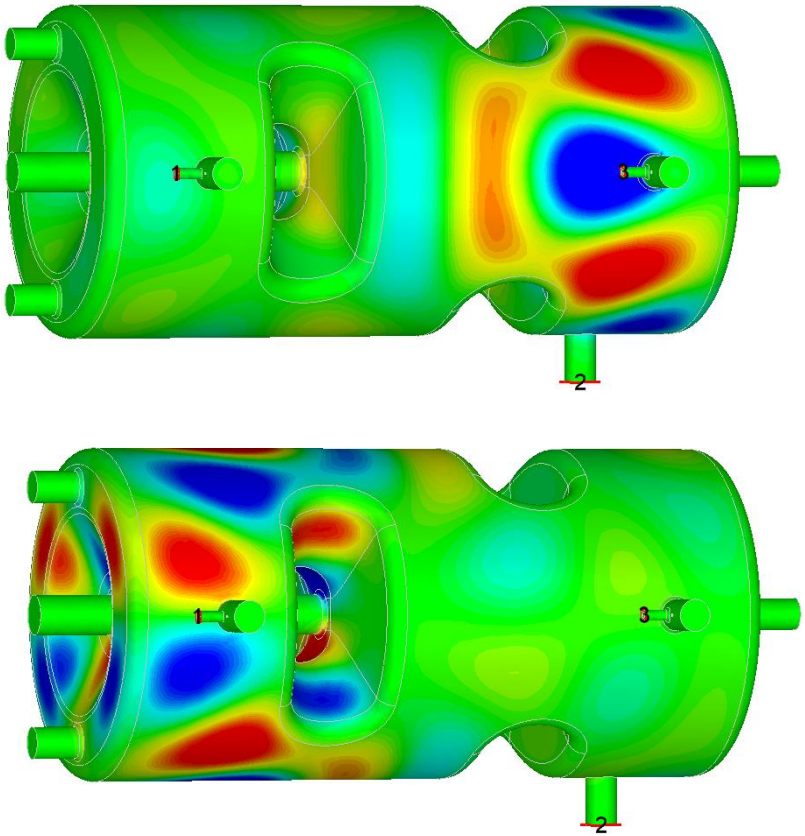




897 MHz Deflecting Mode

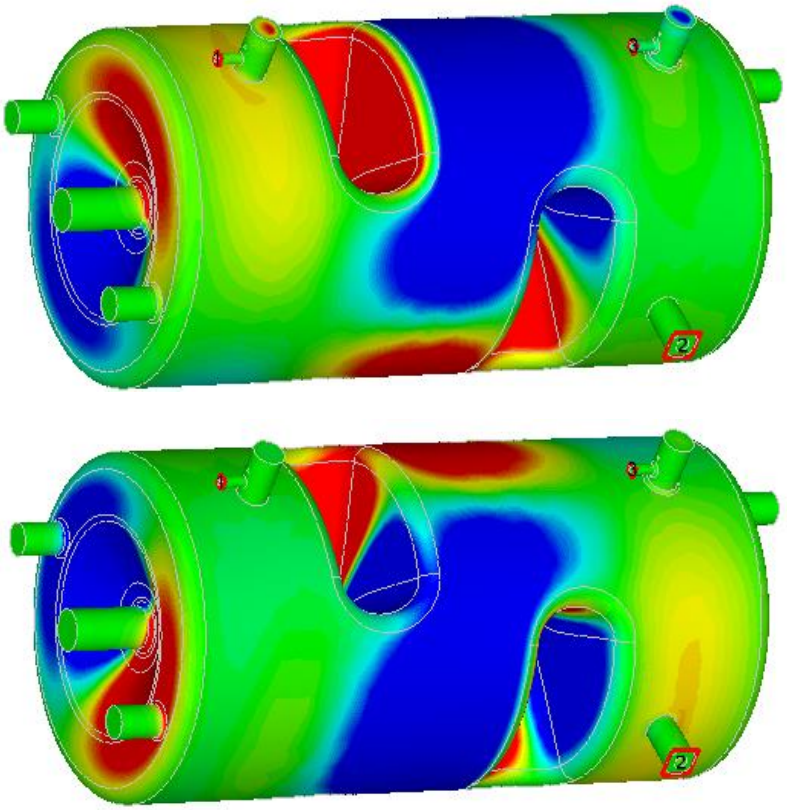
SURFACE FIELDS

Surface electric field



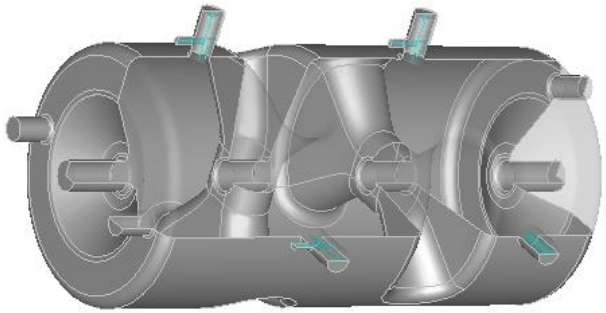
1569 MHz Deflecting Mode

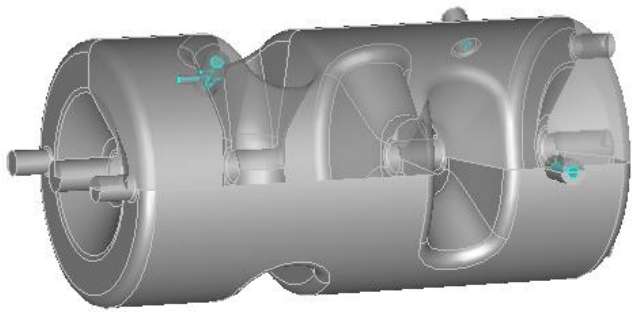
Surface electric field



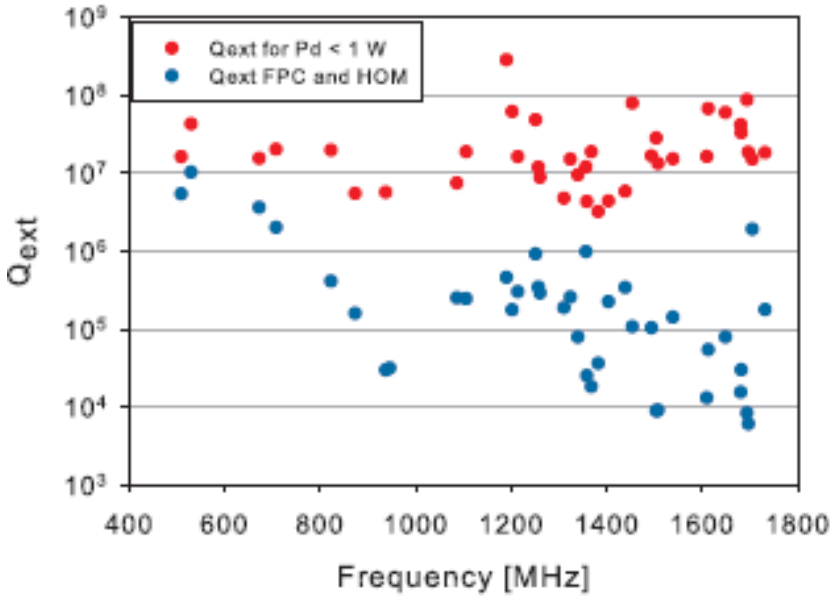
911 MHz Deflecting Mode

HOM DAMPING

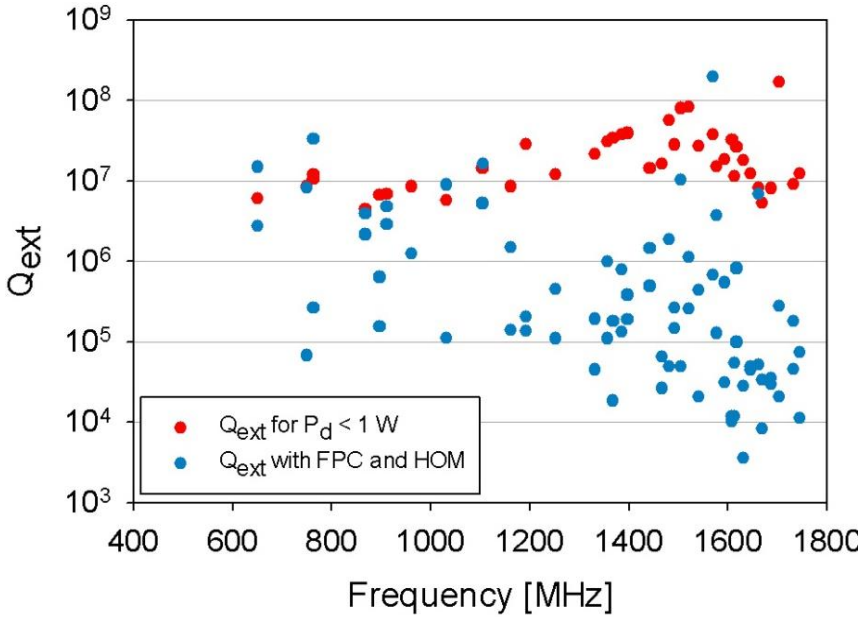




- Moderate damping to keep the cryogenic losses due to HOMs “tolerable.”



Accelerating modes



Deflecting modes

CONCLUSIONS

- Multi-spoke cavities have a complex HOM spectrum
- Symmetry leads to deflection not along one axis
- Both single- and multi-spoke cavities offer a great deal of flexibility in terms of coupler placement (no need to introduce asymmetries to couple in certain areas)
- Many questions still to be explored:
  - What are the beam dynamics and how can the orientation of the spokes be used in our favor?
  - Coupler configurations for most effective damping
  - How will cavity tuning affect HOM spectrum

ACKNOWLEDGEMENTS

- ODU
  - Prof. Jean Delayen
  - Subashini De Silva
  - Alex Castilla
  - Rocio Olave
- Jlab
  - HyeKyoung Park
  - Tom Powers
  - Haipeng Wang
- Muons, Inc.
  - Frank Marhauser
- SLAC
  - Zenghai Li
- LANL
  - Frank Krawczyk